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NEW TECHNOLOGIES AND PROFITABILITY OF HELICOPTERS

J. Andres

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NEW TECHNOLOGIES AND PROFITABILITY
OF HELICOPTERS

Jacques Andres*

Introduction

As a means of transportation, as a tool, or as a weapon, the helicopter meets certain needs. It provides certain functions by carrying out certain missions with respect to profitability criteria. Determination of a mission with all its aspects of performance, safety, and comfort — i.e., determination of which helicopter will carry out a mission — thus results from optimization of a complicated compromise between the costs of tooling to produce the helicopter and the value of the services rendered by this helicopter. Changes in technology progressively move the optimization point by extending the physical and economic limits of performance, safety, and comfort during development, tooling, production, and operation. Choice of any technical option must thus follow directly from as extended an analysis of profitability as possible, taking into consideration all possibilities offered by the state of the art at the moment of selection. /21-1**

*Head, Vehicle Department - Director of Program AS-331, Aérospatiale, P. O. Box 13, 13722 Marignane, France.

**Numbers in the margin indicate pagination in the original foreign text.

Criteria for Profitability

Preliminary Remarks

Because of its special characteristics, the helicopter is a vehicle capable of carrying out a large number of missions which are suitable for it and which no other civilian or military transport can perform, at least in most cases. Among these missions are the transport of loads over broken terrain, mountain rescue, resupply of oil-drilling platforms at sea, rapid deployment of commandos, etc.

But the helicopter is not simply a highly specialized "tool"; it can also compete with certain traditional means of transport over short or medium distances, due to its advantageous performance and lifting capacity.

Despite these qualities, however, this type of aircraft has for a long time been handicapped by its complexity and its quite high operating cost per hour of flight. This is due basically to its characteristics of asymmetry and cyclic variations in rotor operation. The fact that the helicopter should for a long time remain chiefly a military craft at a time, when the idea of effectiveness takes precedence over the idea of profitability, has further aggravated this tendency. For several years now, great efforts have been undertaken by manufacturers for the progressive improvement of these machines, not only in performance, but also and especially in profitability.

In our modern civilization, this idea of profitability tends to become the principal consideration, no matter what is concerned. Before he invests, the user of a product seeks to know the best use to which he can put it, and especially the profit to be gained. And in this modern spirit it is not merely the purchase price which counts, but also what it will cost him to use this equipment and what return it will bring him in the end.

While the profitability of equipment used for passenger trans- /21-2
port, for instance, can be calculated easily, the idea of "service

rendered" is more difficult to figure in a commercial scheme. Thus, certain services rendered apparently have a purely humanitarian aspect, but it is by no means easy to determine at first glance the financial value which can be obtained from them. One example of this is mountain rescue, which often employs extensive operations. Yet studies have shown that a human life represents a very important capital asset, and that it is "profitable" to employ appropriate means to save it. A similar matter is the case of highway intersections whose dangerous configurations results in many accidents. The same type of study shows that in valuing a human life, it is profitable to invest large sums to improve these intersections.

Thus profit, however it is calculated, is a decisive element in the choice of a piece of equipment. As a means of passenger transport or of aerial work, the helicopter can be considered a "tool" — a tool which costs money for purchase and for operation, but which must return profits to the user. Profitability must consequently be a major concern of the manufacturer, just like performance, safety, and comfort.

Concepts of Specific Cost or Cost per Kilogram

Some simple criteria are necessary for the helicopter manufacturer to orient and guide his technical options with respect to criteria for profitability. The concept of "specific cost" or "cost per kilogram of helicopter" is a fundamental point of reference: in particular, the "specific cost price" or cost price per kilogram fabricated, and the "specific operational cost" or cost per kilogram of helicopter in operation.

Specific cost price:

This is the cost of the helicopter to the manufacturer, i.e., the cost of fabrication plus amortization of tooling and research and development expenses, divided by the empty weight of the machine. It includes the cost of the engines, but not the cost of special equipment. The average cost is about 800 F/kg*, and runs from about 500 F/kg for the simplest to about 2000 F/kg for the most complex machines. This does not consider the profitability of the machine, but it does represent the traditional basic idea of cost price for the user.

Specific operational price:

By definition, this is the total cost to the user of the expenses imposed by the purchase and operation of the helicopter during its entire lifetime, divided by the average payload. This specific operational price is determined with much less accuracy and certainty than the specific cost price, because to calculate it one must make many assumptions about the profile and profitability of the missions executed. If it is assumed that the profits from the operation of a helicopter over its whole life (10 years, on the average) exactly offset the purchase and operational costs — hence, with no profit — it can be seen that the specific operation price represents the loss in earnings imposed by one extra kilogram of helicopter. The average value of the specific operational price varies strongly with the type and lifetime of the machine, the nature and number of the missions,

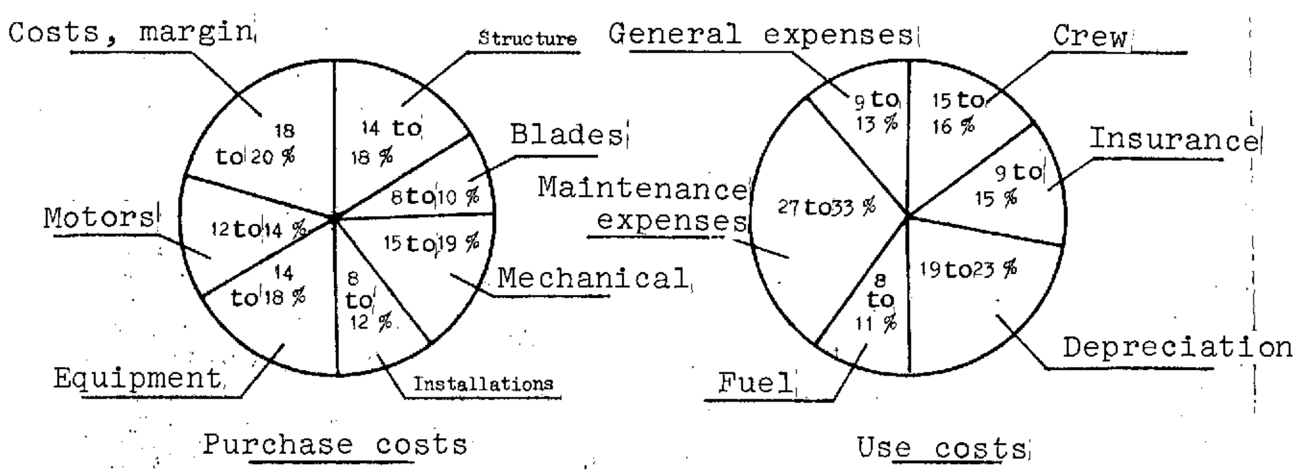


Figure 1. Average distribution of expenses

*Translator's note: 1 French Franc = $.23

etc., but is about 10,000 F/kg, with a range from about 5000 F/kg to about 20,000 F/kg. An example of the former is sling work with an easily maneuverable helicopter; of the latter, passenger transport in a medium helicopter. From the point of view of profitability, the specific operational price is fundamental for the helicopter manufacturer.

Fundamental Characteristics of the Helicopter

The three fundamental characteristics of a helicopter, those /21-3 which determine its missions and, consequently, its profitability, are its performance, its safety, and its comfort. In the following section, we shall attempt to isolate by use of examples the principal criteria for optimizing each of these fundamental characteristics, or — to put it in other terms — to compute the increase in cost for an increase in performance, safety, or comfort using present industrial technology and existing helicopter models.

Improved Performance

Engineering aspects of speed

The progress in performance, particularly in speed, since the first operational helicopters is remarkable. The constant increase in the records illustrates this progress perfectly (although the present capabilities of production machines are slightly lower):

178 km/hr in 1944 by Sikorsky R5A
208 km/hr in 1949 by Sikorsky S52
236 km/hr in 1953 by Piasecki YH21
350 km/hr in 1963 by SA-3210 Super-Frelon [Super-Hornet]
355 km/hr in 1970 by Sikorsky S67

The gains in top speed are obtained by increased power, improvements in fuselage design, and improved parameters of aerodynamic operation and rotor dynamics. (The real solution, above a certain speed, lies more in increasing the lift-to-drag ratio than in increased engine power.) Considerable effort is now being expended in this area by most helicopter manufacturers. Cautious forecasting of the progress to be made in future years leads us to believe that the helicopter will follow an evolution parallel to that of the airplane, and that better lift-to-drag ratios will be obtained. It can be expected that future helicopters will fly at around 350 km/hr, with top speeds on the order of 400 km/hr.

But the increase in speed is expensive — first of all, because it requires extra power. Above 250 km/hr, the power required varies appreciably, as the 2.5 power of the speed, all other things being equal. This implies a considerable increase in fuel consumption, and in the case of a single-engine helicopter without an excess-power engine, the necessity of mounting a more powerful engine. Next, because along with this power increase it supposes improved fuselage design, which in turn implies certain effects on the internal volume, the necessity of retractable landing gear, appropriate fairings, etc. Finally, because it increases the vibratory aerodynamic forces on the blades; this appears as increased fuselage vibration and higher fatigue of the working mechanical components, and consequently implies a much more extensive optimization of the dynamic and aerodynamic characteristics of the blades and the vibrational behavior of the structure.

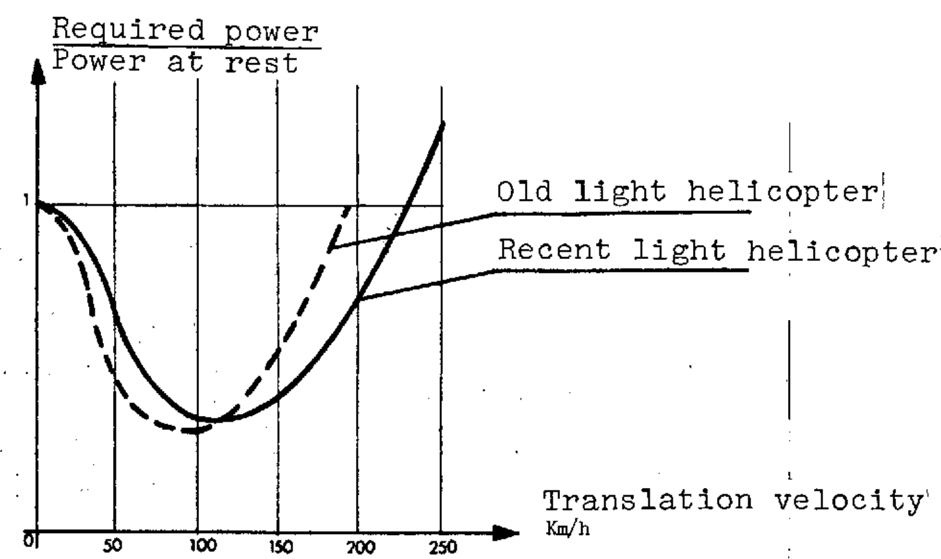


Figure 2. Required power as a function of translation velocity.

Effect on the specific price

It is difficult to calculate accurately the cost of speed to the helicopter manufacturer, but as an example of the order of magnitude it can be said that, for a current light helicopter and existing technology, increasing the economical cruising speed from 200 to 250 km/hr would increase the development cost by 30 to 40% and the selling price of the machine by 15 to 25%, because of the effects produced by aerodynamic and dynamic improvements in the rotor, improved fuselage aerodynamics, optimization of the vibrational properties and general strengthening of the system, and the requirement for a more powerful engine.

Effect on the specific operational cost

Let us take the example of a 7-ton medium helicopter going from 250 km/hr to 275 km/hr for the transport of internal cargo over a distance of 150 km. If the machine is not modified, the increased fuel consumption will neutralize the gain obtained by reduction of the flight time, so the specific operational cost is not reduced, and this operation is not profitable. On the other hand, if the loss due to increased fuel requirements is compensated by adoption of new-generation engines (presently under development; power per unit weight is doubled and the specific fuel consumption reduced a third), the specific operational cost is reduced by more than 10%. This means, in other words, that the helicopter with "new engines" and capable of 275 km/hr will be capable of earning 10% more than the standard helicopter capable of 250 km/hr. If it is assumed that the return to the user is 10% of the total sum invested, this means that such an operation doubles the profits. /21-4

Increased Safety

Very schematically, and strictly from the standpoint of reliability, it is the rule to classify the main essential components of a helicopter into three large categories: those whose failure during flight will endanger the machine; those whose failure may interrupt the mission without endangering the machine; those whose failure will require repairs after flight without compromising the mission. Considering failure mode, there are components which have finite fatigue lives, and those with programmed lives, mainly gears and bearings.

Components with fatigue lives

Reliability has been provided in recent years for components which fail in fatigue through the concept of fatigue life. This idea is based mainly on the fact that fatigue resistance for a family of components and the forces which they bear during flight follow a Gaussian distribution function, and thus cannot take into account the rare cases of manufacturing defects not detected during inspection, abnormal flight conditions, and mistakes in maintenance. The fatigue life of a component is calculated on the basis of flight recordings made under normal flight conditions, together with limiting values obtained from laboratory tests on specimens. These calculations are derived from a necessarily limited number of laboratory tests and flight measurements. The dynamic safety factors are such they they provide a risk of 10^{-6} with 90% confidence. However, while the use of a finite fatigue life with a definite degree of uncertainty is correct for reliability, it is scarcely satisfactory for profitability, since it requires that components which are apparently in excellent condition be thrown away at the end of their "safe" lifetime. This is why the present tendency is to obtain infinite fatigue life for all essential components. This condition imposes constraints during design and production, since it assumes exact dimensioning of pieces and exact knowledge of the forces born in flight, but it has little effect on the overall weight: the critical portions of an essential component make up a very small part of the total volume; the rest is dictated chiefly by conditions of rigidity, of motion to be transmitted, of volume to be contained, of surface to be provided, shape continuity to be maintained, etc.

Studies of the causes of accidents involving our helicopters during flight show that 12% are due to errors in maintenance and 8% to manufacturing defects; the remaining 80% can be charged to human error. To this idea of "safe fatigue life", the concept of "Fail-Safe" has been added in the last few years. Its major principles can be defined as follows: during design, to reduce as far as possible the risk of mistakes in maintenance and the consequences of a mistake in maintenance; to provide redundance of essential components or circuits, which means that an essential function must always be at least doubled, with each single element capable of providing the function by itself; to provide an inspection system which can prevent any risk of loss of function. Applied heavy-handedly, these principles would result in unfortunate consequences, and might even be counter-productive due to the generally increased complexity they would require. Adoption of new techniques, such as <u>layered</u> or laminated materials and research on secondary effects, such as increased vibration in an apparatus produced by the introduction of play into the controls because of flaws in simple elements, or the use of colored sweating liquids, allow Fail-Safe conditions to be met without prohibitive effects in weight. Under these conditions, it is possible to show effects of less than 20% in the weight of redundant parts without any corresponding significant increase in their over-all dimensions. Total compliance with the Fail-Safe principles in the main rotor hub assembly would lead to an increase in weight of 70 kg under these conditions, for a 7-ton medium helicopter. This is an increase of 3.5% in the specific operational cost for the internal transport of cargo over 160 km; the machine is thus 3.5% less profitable. For transport of passengers over 400 km, this number becomes 6%.

Programmed-life components

The philosophy of reliability of programmed-life components, mainly the gears and bearings, has advanced in the same way as that for reliability of components with fatigue lives. At first, there was the idea of programmed life, which required that mechanical components which were apparently in excellent condition, most of which could continue to operate even longer, be disassembled for inspection at strictly specified times. Furthermore, this approach could deal only imperfectly with manufacturing defects which passed inspection, or with maintenance errors. This is why today the idea of programmed life tends to be replaced by the idea of "replace according to condition". Thus, if it is possible to detect and diagnose the deterioration, one can know or predict at every instant the condition of the equipment, the extent of any deterioration, and the optimal moment to act. This change in philosophy assumes that the equipment has been studied and proven with new ideas which pay particular attention to the nature of the presumed deterioration, together with integration of systems for examination and quality control.

In a similar manner, the Fail-Safe concept tends to be introduced /21-5 today into lubrication methods, either by introduction of emergency lubrication or by redundant lubrication systems; tomorrow it may be done by crack detection in gear boxes or by redundant bearings. Application of redundance principles to gears and shafts would lead to a weight penalty of about 30 kg for a medium helicopter, or a 1.5% decrease in the specific operational cost for internal cargo transport over 150 km.

The Price of Comfort

Noise reduction

The noise problem is relatively recent for helicopters, and coincides with the opening and growth of the civilian market. The problem is in fact two-fold: first, the nuisance of external noise when helicopters are operated in urban areas; the sources of this sound are located in the engines and the rotors. The second aspect is the internal sound field, which affects the comfort of passengers and crew; the source of this sound is chiefly the main engine transmission.

As for the external noise, one of the objectives to be attained is a sound level of 90 PNDB (PNDB means "Perceived Noise Decibels" and relates to all frequencies which produce any physiological acoustic disturbance) at a radius of 150 meters around the craft hovering at ground level. This means that there will have to be a

10 to 15 PNDB reduction in engine noise and a decrease of 6 to 7 PNDB in rotor noise from current light helicopters. At the present time, practical accomplishments in combatting external noise are concerned mainly with the engines. The tip velocity of the transsonic compressor generates intense noise with a fundamental frequency of at least 6000 Hz and a spectrum very rich in harmonics. Remedies can combine use of sound-absorbent materials and masking by adequate air-intake geometry. The gains obtained are of the order of 10 PNDB at a cost of about 2 to 3% loss in engine power, which limits the performance range of the machine, especially in altitude. As for rotor noise, corrective action, in general, should be directed toward the aft rotor. A 10% decrease in the velocity of the aft blade tips produces an improvement of 3 PNDB. In the case of the main rotor, improving the profile and optimizing the plan form of the blade tip will provide improvements of 3 to 5 PNDB by increasing the Mach number for drag divergence and diluting the tip vortex. A greater improvement, 10 to 15 PNDB, would require a decrease in the tip velocity of the main blades; this would in fact mean a new design of the main rotor, and in any event a significant sacrifice in performance.

With respect to internal noise, 80 dB SIL (dB SIL means "Decibel Speech Interference Level" and refers to speech frequencies from 500 to 4000 Hz) is a noise field which requires the voice to be raised in order to converse at more than 20 cm distance. If this is compared to the 70 dB SIL of commercial aircraft and to the 85 dB SIL of single-engine light planes, it can be seen that the sound field to be achieved is at most 80 dB SIL. This means that in light helicopters there must be a reduction of 10 to 15 dB SIL, and of 20 to 25 dB SIL for medium helicopters. By current methods of acoustic screening, this can be accomplished by adding 1 to 1.5% to the total weight of the machine. During design of the transmission, based on appropriate gearing technology and with judicious choice of the natural frequencies of the shafts and of the acoustic qualities of the gear boxes, this weight penalty can be held to 0.25 to 0.3% of the total weight, but this technique has not yet been mastered at present.

Vibration reduction

The fuselage of a helicopter vibrates mainly at a frequency of bΩ = the number of blades in the main rotor × the rotational speed of the rotor. For a given helicopter, this frequency is generally a constant (except for unusual autorotation conditions), and will fall between 16 and 24 Hz. To facilitate analysis and to standardize vibration estimates, the measurements of vibration accelerations must be made: a vertical dynamic acceleration of 0.1 g at 18 Hz is considered "very good". (For reference, although new American programs have considerably more severe requirements, commonly-accepted standards are 0.15 g up to cruising speed, 0.2 g up to top speed, and 0.3 g in the transition region.) In addition to the vertical acceleration terms, the vibration "level" is made up of transverse and longitudinal terms as well, generally of lower amplitude than the vertical term. The vibrations of the walls, flight instruments, and controls which make up the vibrational "ambient" behave in a similar fashion.

Preoccupation with providing an excellent vibration level is not /21-6
new in the helicopter industry. It is during the development stage that improvement of the vibration level is expensive; expenditures for this problem can vary between 10 and 50% of the whole, depending on the extent of the intended flight regime and the difficulty of the

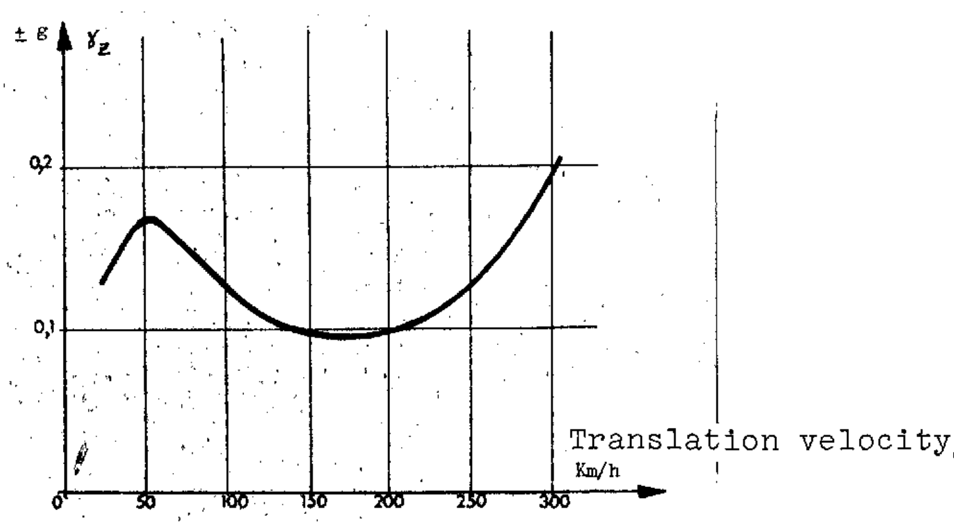


Figure 3. Variation of the vibration level as a function of speed.

trade-offs to be made. Improvements may be made in the rotor blades by minimizing the applied aerodynamic forces and their transfer from the blades to the hub, in the transmission case by adequate suspension (i.e., by making better use of the inertia of the case by either active or passive methods), and in the fuselage by optimizing the vibrational characteristics of the structure. Such work comes into play right at the start of machine design, with greater effectiveness as the amount of experience accumulates and the methods of calculation become more accurate, then in the laboratory as soon as models or scaled components allow, and finally on test stands and with the prototype in flight.

Up to about 0.15 g, it can be said that the vibration level does not have any appreciable effect on the manufacturing cost of the machine if the development work has been carried out in this spirit: in the long run, it is not more expensive to manufacture a blade correctly tuned between two exciting frequencies than it is to make a blade tuned to only one. Beyond these values, and with the present state of our knowledge and our means, it becomes necessary to use more or less expensive refinements.

Conclusion on the price of comfort

Conquest of the civilian helicopter market means that the passenger on inter-airport links, the company president on "business" trips, etc., must be offered internal and external appearance, comfort, and environment which are comparable to those the customer is accustomed to find in airliners, in corporate aircraft, or in luxury automobiles.

To give the cabin of a light helicopter, a "five-seater" for example, passenger space identical to that of a Rolls or Mercedes-type automobile in height, length, and width, structural modifications to a current helicopter would cost some ten kilograms, and the increased cabin cross-section would increase the drag of the machine by 8 to 10%.

In addition, the interior finishing needed to obtain a good sound and vibration environment in accordance with the rules of esthetics and the regular accommodations of the automobile or VIP aircraft cost some thirty kilograms by traditional methods. These requirements increase the specific operational cost by about 10%. Likewise, to give the cabin of a medium helicopter a level of comfort required for the usual transport of passengers, an increase in the specific operational cost of about 10% must be accepted.

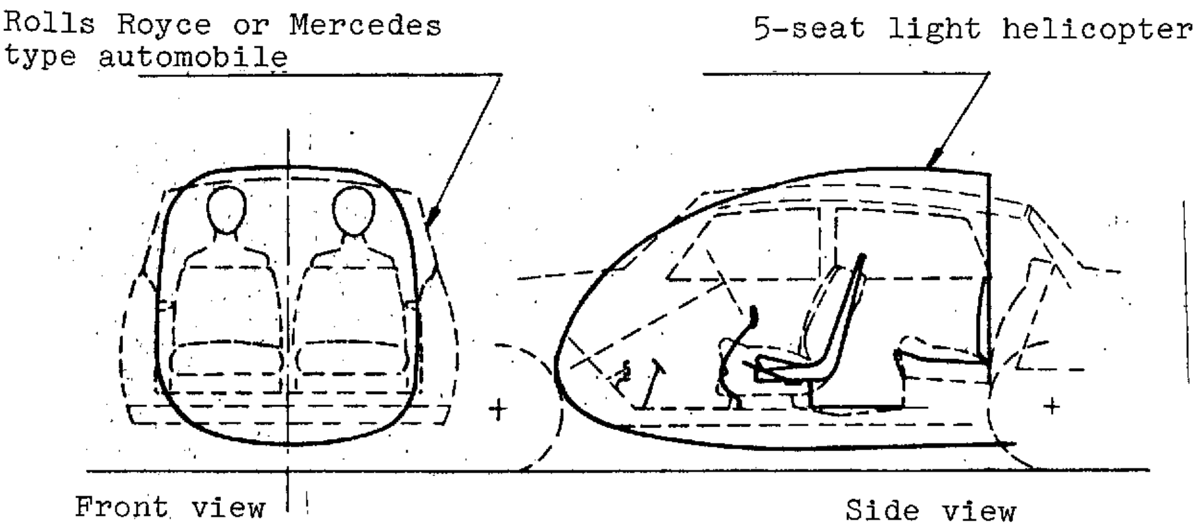


Figure 4. Comparison of internal arrangement of a light helicopter with that of an automobile.

Application of New Technologies

The preceding chapter discussed existing helicopters — that is, /21-7
those designed a few years ago and resulting from a compromise among the state of the art, the ideas of profitability, and an extrapolation of the operational needs of that time. The new needs in performance, comfort, and reliability which have appeared since then lead to a certain "disequilibrium" between existing equipment and the desired equipment, because technologically no improvement can be made without dire effects on weight and cost. In trying to calculate the cost of these improvements, we have seen that each attempt with a constant technology is paid for by an increase in the specific cost

and the specific operational cost. The necessity of introducing new technologies to attack these points of optimization, and thus improve cost effectiveness, is thus clearly apparent. (It should also be noted that introduction of new technologies also often occurs due to the pressure of the engineers themselves.) In the following section, we shall try with the aid of a few examples to define the policy of Aérospatiale with respect to new methods of calculation, new concepts, and new materials.

New Methods of Calculation

Preliminary remarks

Especially in the areas of rotor aerodynamics, vibrations, and the behavior of components which may fail by fatigue, fundamental areas in helicopter technology, new methods of calculation which have appeared recently allow total participation of the computer at each stage of helicopter development: design, research, laboratory testing, and flight tests. One thus obtains a better analysis of the engineering conditions to be satisfied, a more certain and more precise choice of the corresponding technical approaches, and a more rapid and more complete understanding of the phenomena encountered. In certain cases, it is even a new dimension which is suggested — that is, the possibility of carrying out investigations by calculation which would have been impossible without these new methods. We shall give three example of the application of new methods of calculation.

Dynamic optimization of blades

From an aerodynamic standpoint, a helicopter blade can be considered to be a wing moving with respect to the air, with rotational motion about the rotor shaft and translational motion as the helicopter moves ahead. The aerodynamic forces applied to helicopter rotor blades consequently contain large periodic terms resulting from the combination of the translational velocity of the machine with the rotational velocity of the rotor. These sinusoidal terms in the applied aerodynamic forces thus have frequencies which are multiples

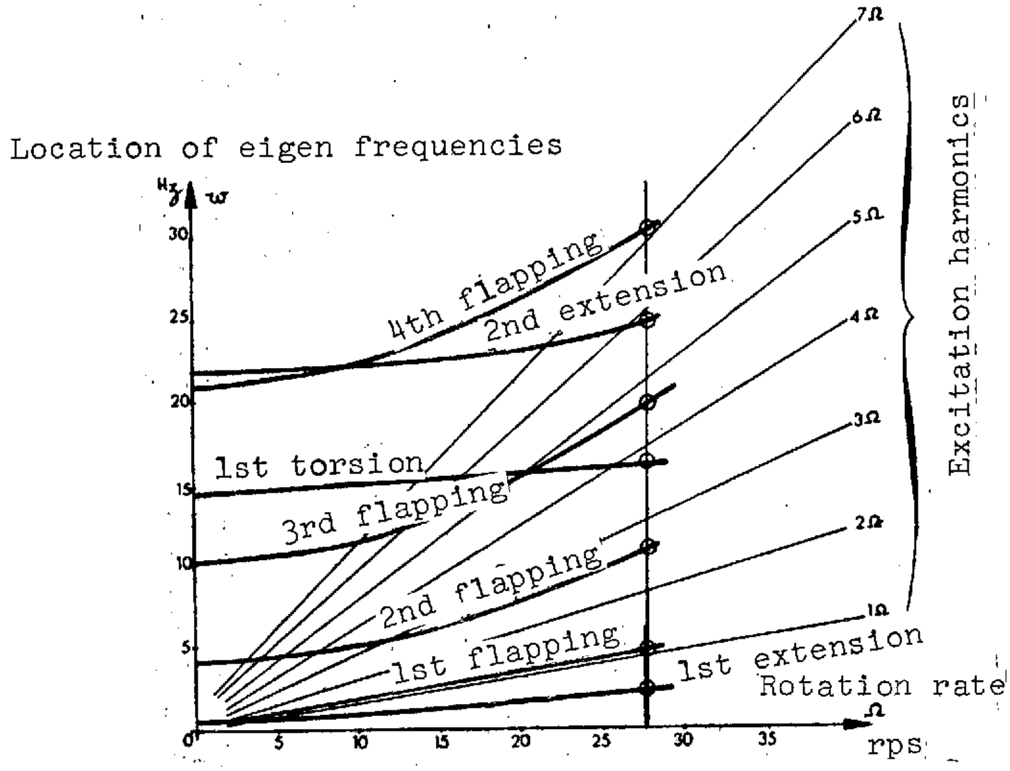


Figure 5. Eigen frequency diagram of the blades

of the rotational velocity of the rotor. From the point of view of dynamics, the blade is a very long and very flexible beam which is stretched by centrifugal force during operation. It thus has very many natural modes in flapping, extension, and torsion. The natural frequencies of these modes with respect to excitation harmonics determine the amplification or damping of the forces applied to the blade. Each blade transmits to the rotor hub the aerodynamic forces applied to it, through its "transfer function".

The dynamic optimization principle involves finding the distri- /21-8
bution of mass and stiffness along the blade span which will allow the minimum force to be transmitted to the hub for all the main harmonics which excite flapping, extension, and torsion, with the severe restrictions imposed both by aerodynamics on rotor radius, chord, profile thickness, twist, etc., and by conditions of static strength and fatigue resistance. All these conditions leave little margin for maneuver with traditional blade technologies. The appearance of glass-fiber resin and carbon-fiber resin materials opens very wide

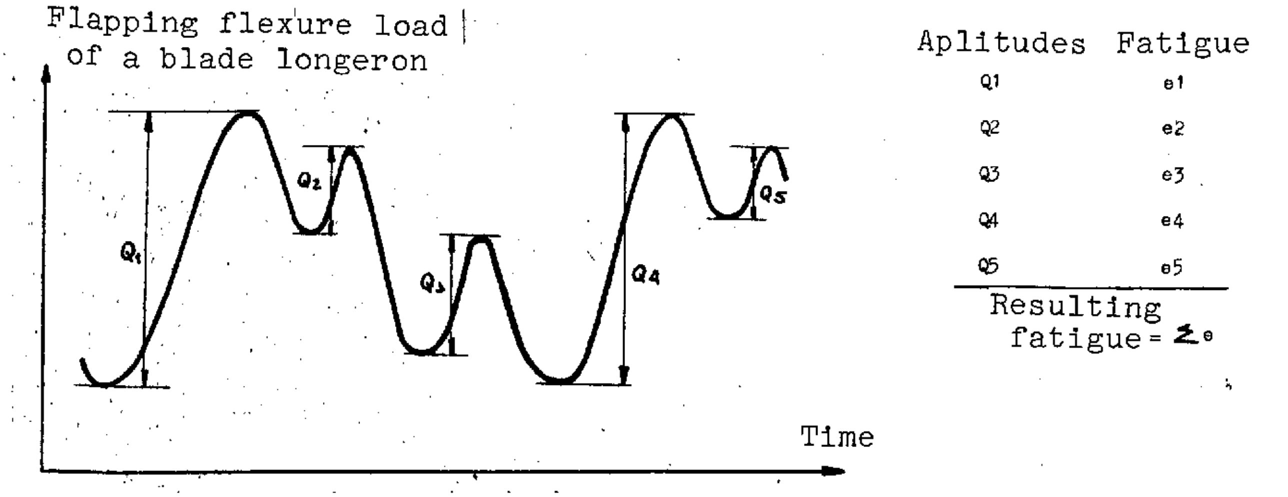
perspectives for action on the mechanical qualities of materials and in their flexibility of application, and allows reconciliation of a rather large number of requirements. In the dynamic optimization method for blades, the responsible engineer seeks the optimum values by direct dialog with the computer. The calculation starts with a basic configuration of the blade in mass and stiffness. The conditions of optimization can be the position of natural frequencies with respect to exciting harmonics, or better, they can be the transfer functions of the applied aerodynamic loads. By linearized calculations, one seeks, for example, the variations in the natural frequencies obtained for small variations in the distribution functions of the blade. In the present program, there is provision for simultaneously modifying up to ten sections out of a total of thirty, in arbitrary order; this can be done repetitively and cumulatively. When the modifications have a non-linear effect, the computer signals the fact. It is thus possible to store basic distribution functions and natural frequencies and to calculate directly the new frequency diagram which replaces the starting one.

This method of calculation, starting with knowledge of the applied aerodynamic forces and taking advantage of the property variations obtainable by glass- and carbon-resin technology, ought to allow optimization of blade transfer conditions, to allow us to obtain low vibration levels and low constraints right from the start of prototype development. This would lead to a considerable reduction in the delays and expenses of development.

Automatic load analysis

From the asymmetric and cyclic operation of the rotor, the various components of a helicopter are subjected to sinusoidal forces, and work under fatigue conditions. It is thus necessary to calculate the fatigue life of each element under operating conditions.

Standard methods for calculating fatigue damage are based on the establishment of an outline of the machine's flight based on the principal steady or changing flight configurations required by its



mission, and then the determination of the amplitude and frequency of dynamic loading on each essential component for each flight configuration. These methods of calculation require manual analysis of recorder charts showing loads during flight, a very tedious procedure susceptible to human error in interpretation of the phenomena.

Aérospatiale has developed a method for automatic load analysis based on acquisition of successive peak-to-peak amplitudes and their comparison to pre-selected reference damage parameters. The unit damages calculated from Woehler curves based on laboratory tests are then processed by use of Miner's cumulative-damage law, either directly in flight by an on-board computer or via telemetry, or after flight from magnetic-tape records of the loads.

This new method of analysis brings to prototype development the possibility of knowing at each instant during flight the growth of damage to each of the principal components; at the start of series production it is now possible to obtain very complete statistics on the loads applied during transitional flight configurations, and generally to have a much more correct evaluation of the damage really suffered in flight: in other words, a more accurate measurement on the working components and a more correct value of their fatigue lives.

Thus, over the whole range of operations for monitoring in-flight damage or for calculating fatigue lives, there has been a considerable gain in time (the overall time has been cut by a factor of five), as well as increased precision and reliability which allow either a reduction in the weight of essential components or an increase in their lives by discontinuance of needless safety factors which were the fruit of ignorance. /21-9

Structural analysis

Always basic to strength and vibration calculations is a schematization of the system to be calculated. This schematization becomes more difficult or more imprecise as the system becomes more complex. For the fuselage of a current medium or heavy helicopter, idealization by standard methods is illusory.

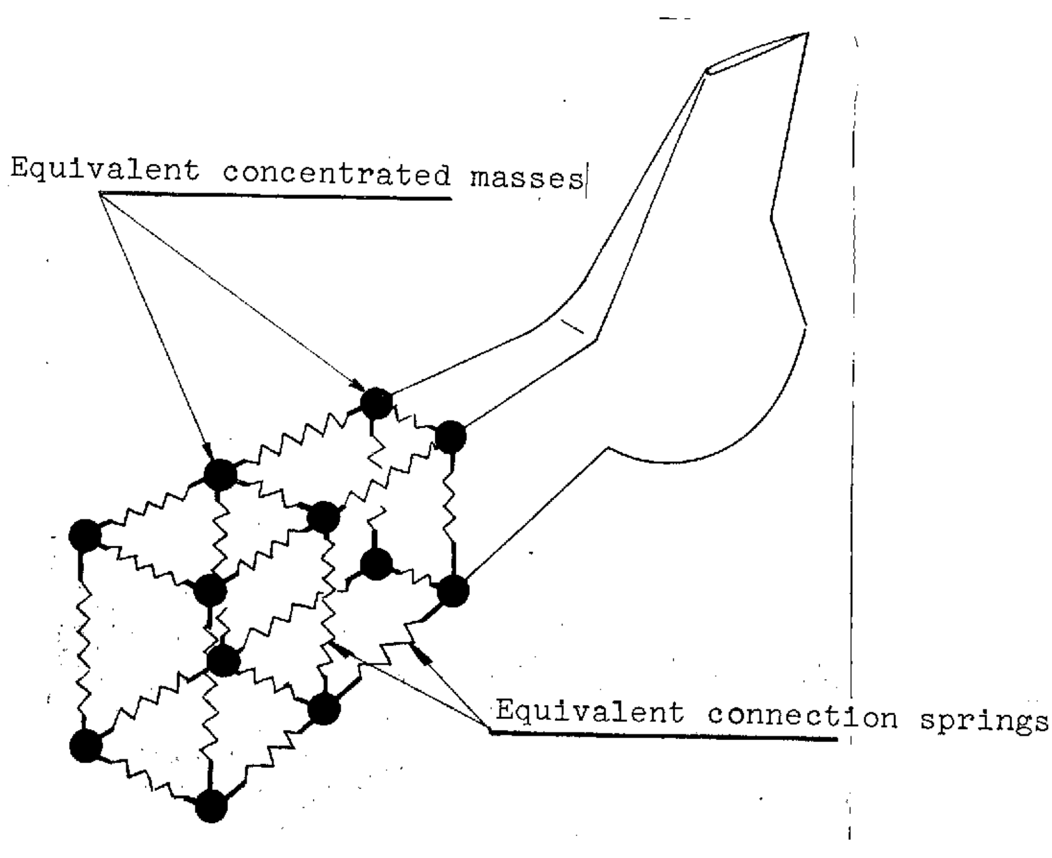


Figure 6. Schematisation of a structure by a collection of equivalent concentrated masses and springs.

Based on finite-element methods, structural analysis is employed in two areas: analysis of loads supported by structural components or parts with complex shapes, and study of structural vibrations. It consists chiefly of substituting for the real structure an equivalent system composed either of simple elements such as tension bars, beams in flexure, triangular plates, etc., for strength analysis, or simple pure-mass elements interconnected by simple purely elastic elements for vibration analysis. The fineness of the divisions is a function of the complexity of the structure, the precision desired, and the capacity of the computer used.

Applied to complex-shaped mechanical parts, structural analysis allows one to obtain an excellent approximation to the real load distribution, so that there are accurate determinations during design and a reduced volume of tests during measurement of the loads and during proving. Applied to structures during the project stage, solution of the dynamics equations allows determination of the normal modes and frequencies of fuselages and the extent to which they couple with the rotors, and so considerably reduces the volume of vibration tests on the prototype, facilitates interpretation of results of flight and laboratory tests, and guides developmental modifications more effectively. The gain in fuselage vibration development is of the order of 50%.

New Concepts

Preliminary remarks

In an attempt to reduce both the industrial cost price and the operating cost, Aérospatiale has, for a number of years, applied its efforts to investigation of new ideas better adapted to rational utilization of equipment.

Window-type aft rotor hub*

Among the techniques which have been studied to reduce costs /21-10 and increase reliability and safety, one of the most interesting is adoption of a window-type tail rotor* to replace the standard aft rotor. This rotor, operating inside a duct, is of especially simple design since it uses blades stamped from light alloy with infinite fatigue life, interchangeable without adjustment, and articulated in pitch on maintenance-free plastic couplers. Its remarkable reliability, together with almost zero required maintenance, makes it a very economical system. Thus, its effect is to reduce maintance costs by 50 to 75% with respect to the costs for a standard aft rotor.

By designing it entirely housed within a projection of the tail beam, the rotor is made very safe to operate, since it is completely protected from striking trees, objects on the ground, or equipment when landing, while maintenance personnel on the ground are also protected. This advantage thus appears as an economy in terms of accidents to personnel and repair equipment. In addition, the original design of this device allows removal of de-icing systems, which are customarily heavy and burdensome in other types of aft rotor. Other advantages are obtained in performance: practically zero power consumption in translational flight, better general lift/drag ratio of the apparatus, suppression of blade instabilities, capability of continued translational flight in case of damage to the aft rotor, thanks to the find surface which acts to prevent fuselage rotation.

Modular design

Another source of economy to the operator consists of modular design of the mechanical assemblies. This idea consists of dividing the assembly under consideration into a certain number of different easily-disassembled modules, each of which can have a particular programmed life. This allows a mechanic to work rapidly on a module and

*Translator's note: Aft rotor installed in a round opening in the tail. See Appendix.

replace it by another one in operating condition without inactivating the equipment for any appreciable time. The chief engine manufacturers for commercial aviation have been making their engines in this way for some time, thus allowing airlines to save important sums of money, partly by avoiding long ground time for their equipment, and partly by reducing the size of their stock of repair parts, which is thus limited to a few modules and not entire engines. It should be pointed out that the time to exchange a module should not exceed two hours.

Still there has been little application of this concept to helicopter mechanics. For its part, Aérospatiale means to apply it to certain components, in particular to main transmission cases and to rotor hubs, which are complex, difficult assemblies. In this way, having the possibility of working on certain modules himself, the operator will have greater availability of his equipment and can avoid returns to the factory for repairs, which are always long and expensive.

Modular design is a logical method for operating equipment. It tends more and more to supplant the traditional replacement of mechanical assemblies, programmed or not, which up to now has been a heavy handicap for civilian and military operators in terms of profitability and availability.

"Replace by condition"

The idea of "replace by condition" tends to replace the idea of "programmed part life". Equipment used normally according to the needs for which it was created can deteriorate for different reasons: wear, corrosion, fatigue, aging, unsuitable environment, poor maintenance, etc. Very particularly for helicopters, and especially for the principal mechanical assemblies, it is important to know until what moment one can continue to fly a component which has started to deteriorate, without any compromise in safety. In the present method, since it is not possible to know this threshold exactly, operating periods (part lives) are defined, at the end of which the mechanisms are systematically removed and sent off for overhaul. These part lives are defined by calculation, by fatigue and strength testing, and by experience obtained on similar equipment. In general, the beginning life is of the order of 300 hours; this is changed on successive blades up to values of 1500 to 2000 hours, depending on the condition of the parts examined during overhaul. This method is long and penalizes the user financially because he must replace his mechanical assemblies at fixed periods without being able to know their real conditions with any certainty, and he must have large stocks of replacement parts, especially when the part lives are low.

In addition, this method often brings about unjustified returns to the factory, in which the equipment would still be able to operate satisfactorily for many hours.

From the financial point of view, with respect to availability of equipment and to direct operating costs, the ideal situation for the operator is thus to be able to know at every instant the condition of his equipment, the extent of any deterioration, and the moment which it will be convenient for him to choose for replacement . . . all the while safeguarding safety. We thus arrive at the concept of "replacement by condition", which ought to become very important in the next few years. Application of this new method requires that the equipment be previously tested, calculated, proved, and used under certain conditions, in particular:

- all components must be designed for infinite fatigue life;
- the probable programmed life calculated must be at least 2000 hours;
- the equipment must be studied so that deteriorations can be detected, diagnosed, and watched without ambiguity.

Detection and diagnosis of deterioration can be accomplished only with methods adapted to the nature of the assembly. For transmissions, we can consider the following example: analysis of particles from the magnetic plug and the oil filter, spectrographic analysis of oils, temperature measurement at certain components, noise /21-11 analysis, vibration detectors, measurement of certain clearances, endoscopy, etc. These techniques can be difficult; it is thus desirable to use them with discretion and to strike a cost/effectiveness balance at all times. Aircraft companies presently use this method on new-generation engines, and it is certain that their investments in this system are amply compensated by the resulting gains in equipment utilization.

Aérospatiale thinks that it is possible to apply this idea of "replacement by condition" efficiently, at least for the main mechanical assemblies. It is presently being used in the study of new equipment.

Infinite fatigue life of essential components

The fatigue lives of essential components of an aircraft are calculated from a flight spectrum, the real forces born by the structure or the mechanical assemblies during the different phases of flight. Up to the present time, it has not been easy during the study of a new machine to know *a priori* and accurately the different flight spectra which might be encountered during its existence. This uncertain knowledge consequently limited some lives to relatively low values and had effects on operating costs which were not insignificant. It is interesting to note that in calculating direct operating costs, the item "parts with fatigue lives" contributes about 10%.

The way to decrease operating costs is thus to get rid of this item — to give infinite lives to essential components. Today, better knowledge of the forces born during flight (progress in methods for theoretical calculations, progress in measurement methods and methods of data processing) give a better definition of the essential parts subject to fatigue, right from the design stage. This better knowledge of forces, together with progress made in the statistical definition of flight spectra, allows very long lives to be obtained — really unlimited — right from the start of series production.

Operation of mass-produced equipment

In aircraft construction, use of equipment or material of "aircraft quality" has been imperative for a long time. Certification of this equipment and material is made under the responsibility of the Official Services for Aeronautics. To insure the safety of a mission, it is certainly normal to use safe, operational, and reliable equipment. It would be unthinkable to go up in a machine whose components had not undergone tests and inspections corresponding to a certain mark of quality. However, many machines have exorbitant price tags because of their aeronautical "docket" and their manufacture in small numbers. Except for very sophisticated equipment with a high degree of specialization, it is certain that a large number of machines could be mass-produced, like the automobile.

We believe that important economies could be realized in this area, since the item "equipment" represents 12 to 15% of direct operating costs and 18 to 23% of the cost of a medium-tonnage machine. The differences in price between automobiles and aircraft are considerable; the general rule is 1 to 5, but one sometimes finds a ratio of 1 to 10 and even 1 to 20. It is thus desirable to change the philosophy of choosing this equipment. It particular, it is desirable to create categories corresponding to the function filled by the piece and the role it plays with respect to flight safety. Several categories could be made for which loss or deterioration of the part:

— would result in destruction of the craft;
— would halt or shorten the mission;
— would have no effect on the mission.

In this manner, equipment which did not bear directly on flight safety could be subject to limited certification based on some tests of proper operation on test stands or in the machine, and would not carry over large plus-values to the sale price. Likewise, certification of materials entering into fabrication of certain equipment or installations could follow the same procedure. It must, however, be pointed out that many automobile parts are generally heavier than those for aircraft (but also stronger). When one understands the importance attached to the weight factor in aeronautics, one can see that it will be necessary to strike a serious balance among price, weight, and performance before proceeding to the final choices.

New Materials

Elastomer-metal laminates

In the main rotors of standard helicopters, the blades have three degrees of freedom where they are attached to the hub, provided by three orthogonal joints about which they oscillate periodically. These joints are made with ball or needle bearings.

Replacement of these elements by elastomer-metal laminate blades /21-12
in which movement of the bearing is replaced by elastic deformation allows hope for a large improvement in the cost price:

— by a decrease in the number of parts (replacement of one or more bearings and their gaskets and lubrication systems);

— by simplification of parts (reduction in number of precision of machining steps).

Looking farther ahead, we can imagine hubs which use blades laminated in original ways for their intrinsic qualities, and not as replacements for standard components. The price thus could be reduced very much more. All these simplifications also would bring about weight reductions, which could be very large. In operation, use of laminated blades could produce spectacular cost reductions. These blades require no maintenance (no consumable constituent, no leakage problem). In addition, they are designed to have long lives and have no danger of abrupt breakage. Simple visual inspection is sufficient, and can be performed without disassembly. At the same time that savings thus are being made in maintenance, the availability of the machine increases correspondingly, and the two aspects bring about a considerable reduction in operating costs.

Viscoelastic materials

The classical main rotor hub usually has a hydraulic damper for controlling the extension motion of the blades. In more modern semi-articulated or rigid hubs, it is necessary to introduce a stiffness element in parallel with the damping in the extension plane, with a well-determined damping/stiffness ratio.

In analogy with the general suspension problem, we can conceive of a system with separate functions: spring mounted in parallel with a hydraulic damper. Such a concept using classical elements leads to a complex, heavy and inconvenient system. Viscoelastic materials represent an elegant solution to this problem. The two functions can be provided by one single deformable element. The damping/stiffness ratio and the requirement for having essentially constant characteristics within the temperature range utilized, provide criteria for selecting the silicon elastomer.

This concept is much simpler than the elements which it replaces. This viscoelastic damper results in a substantial decrease in the cost price. In addition, this element can be incorporated in a more compact and simpler hub. It is cheaper as well. This is almost impossible to do with classical systems. Here again, the greatest cost savings are in the operational costs. The viscoelastic damper is designed for essentially infinite life and requires no maintenance at all. Simple visual inspection is enough.

"Glass resin" or "carbon resin" layered materials

We have said that helicopter rotors are simplified by eliminating the classical design in which the hub rests on bearings. This is replaced by elastic elements. These elastic elements are the laminated or self-lubricating blades and the large span deformable elements. The usual metallic materials are difficult to work with in this case (large stresses because of the great rigidity and sensitivity to notches). By using glass fibers imbedded in an epoxy resin matrix, light solutions to these problems can be found which are also advantageous from the hub fatigue standpoint. Using this principle, semi-rigid hubs with deformable arms have been developed, as well as blades which are flexible with respect to flapping which can be used with rigid hubs or semi-articulated hubs. The "glass resin" or "carbon resin" layered materials have a remarkable flexibility (or stiffness) which resists fatigue very well.

Glass fibers are the best material from the point of view of the fatigue resistance/elasticity modulus ratio, for obtaining deformable working components. This is why the "Aérospatiale" blades of this type have an infinite lifetime.

The layered materials also have the following advantages: orientation of the fibers along the stresses; very slow progressive degradation of the material and apparent degradation of the material; no sensitivity to notches.

Carbon fibers are preferred when a high degree of stiffness is required for a small mass and for high stresses. This is used for stiffening the main blades against extension or for producing transmission axles.

The following difficulties also hamper the development of these materials: price, especially for carbon, the cost of glass is relatively cheap at this time, also the working costs are high. A great deal of effort must be made before the prices can be reduced for profitable series production.

Reinforced teflon

Teflon is one of the organic materials for which the friction coefficient is a minimum. This means that it can be used to replace gears under certain conditions, and there are many weight advantages. Also maintenance is economical. But its crush resistance is small. Two procedures have been proposed for giving it the desired mechanical characteristics: on the one hand, by using it in the form of a very thin film (a few microns); however, this technology is relatively rarely used because the application process is a delicate one. The covering is fragile /21-13 and the surface must be very clean in order to apply this treatment. On the other hand, it can be used in the form of reinforced teflon with a thin friction layer (5/100 to 1/10 mm) of a composite powder material, of fibers or of tissue imbedded in a teflon matrix.

Self-lubricating journal bearings can be used in the hub articulation members with a small clearance and when the friction forces do not effect the piloting or the dynamic behavior. This is the case of extension articulations. As far as their application to flapping articulations or incidence articulations are concerned, one must be careful because the friction forces on the dry blade are about 10 times higher than for equivalent ball bearings. This has a direct effect on the control forces. Also, the motions are larger and can lead to parasitic heating. In addition, reinforced teflon blades have a "settling" of the friction layer which occurs during the first few hours of use, which can lead to parasitic play in the bearing.

Conclusion

We have given a few directives on the problem of helicopter profitability. The limits of this study were imposed by the following.

- the requirement for considering actual helicopter missions.
- the à priori importance of comfort and safety dictated by present day tendencies, without any exact knowledge of their influence on profitability.
- reasoning based on the helicopter itself without reference to the profitability of other concurrent possible means of transportation.

At the present time we only wish to estimate the cost and the consequences of concepts which can be used, starting with the present helicopter configuration. We wanted to respond to the requirements which are now developing. We wanted to demonstrate the advantages of new technology of which the helicopter is an example.

We believe that helicopters have now entered an era in which they will demonstrate their efficiency and profitability.

APPENDIX

SLIDES FROM THE CONFERENCE

PLAN OF THE LECTURE

Profit criteria

Optimization between costs of equipment fabricated and the value of the rendered services.

Concept of "specific price" or "price per kilogram"

Cost of helicopter progress

Increase in performance

Increase in safety

Improvement in comfort

New technology inputs

New methods of calculation

New concepts

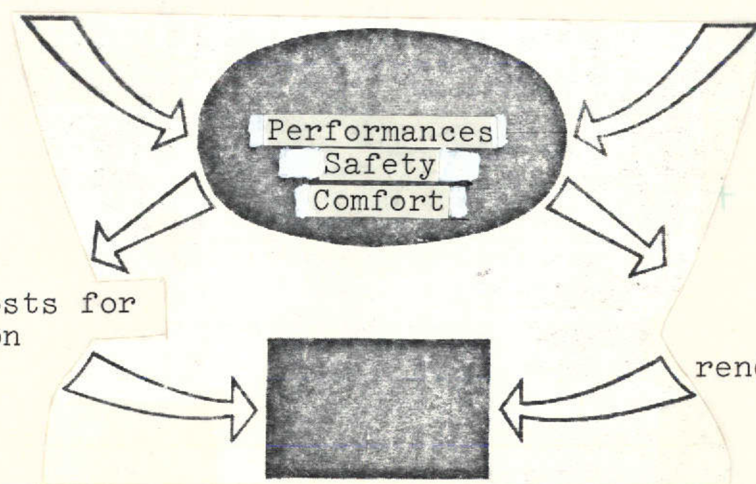
New materials

Slide 1

PRODUCTION LOGIC OF A HELICOPTER

Technical possibilities

Requirements

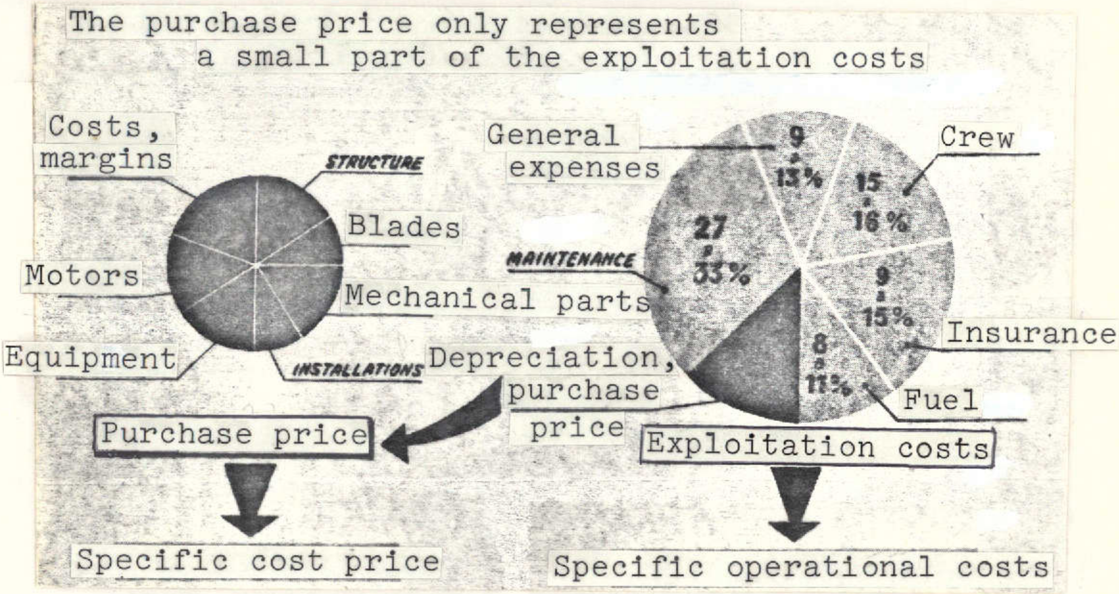


Purchase costs for exploitation

Value of rendered services

Slide 2

COSTS OF HELICOPTER



Slide 3

SPECIFIC COST PRICE

This is the cost price of a device referred to a kilogram of manufactured material.

$$\text{P.R.S.} = \frac{\text{Cost of fabrication}}{\text{Mass of empty device}}$$

- Study costs
- Equipment
- Labor
- Material
- Production
- General costs

Price varies between = 500 F/kg for simple units with long production runs

2000 F/kg sophisticated units with small production runs

Slide 4

SPECIFIC OPERATIONAL PRICE

This is the cost of a device over its complete lifetime, divided by the average payload.

$$P.S.O. = \frac{\text{Total exploitation costs}}{\text{Average payload}}$$

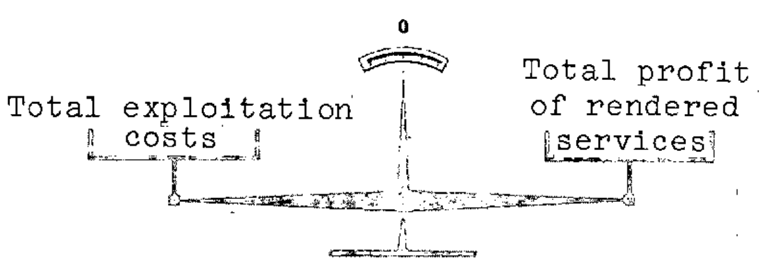
Price varies from:

- 5,000 F/kg sling work with a light device (2 tons)
- 15,000 F/kg internal freight transport with medium helicopter (7 tons)
- 20,000 F/kg passenger transport with medium helicopter (7 tons)

Depends on the mission, number of flight hours per year (1000 hours), Lifetime of the machine (10 years)

Slide 5

FIRST SIGNIFICANCE OF THE SPECIFIC OPERATIONAL PRICE



One excess kilogram of structure = 1 less kilogram of payload

Each kilogram of structure saved represents 15,000.00 F additional return.

During the lifetime of a medium 7 ton helicopter for internal freight missions, for example.

Slide 6

SECOND SIGNIFICANCE OF THE SPECIFIC OPERATIONAL PRICE

Benefits = 10% of the total profit of the services rendered, for example:

- An increase in 10% of the specific operational price results in a cancellation of the benefits.

- A reduction in 10% of the specific operational price results in a doubling of the benefits.

Slide 7

FUNDAMENTAL HELICOPTER CHARACTERISTICS

From the point of view of the mission, a helicopter is defined by:

The possible performance range:

Velocity

The degree of safety:

- lifetime
- potentials

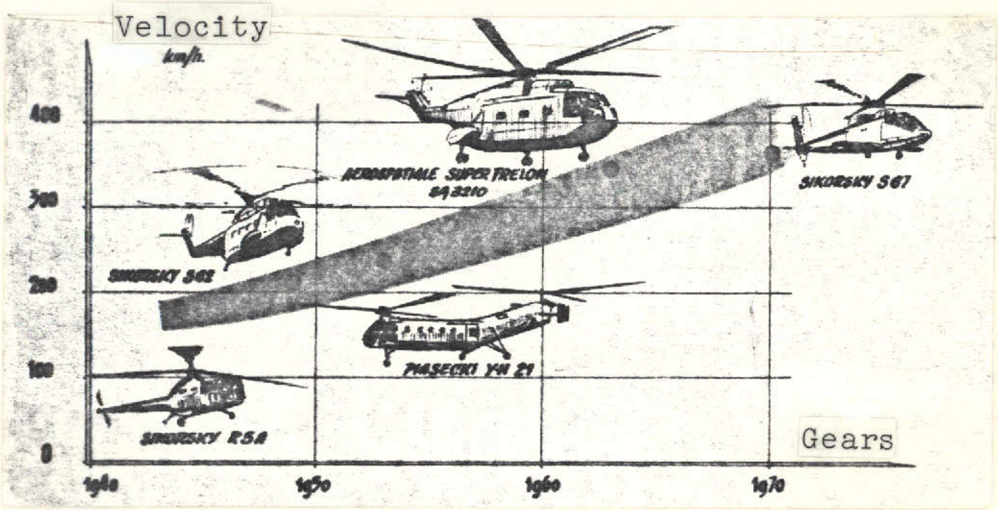
The degree of comfort which it provides:

- Noise
- Vibrational level

Slide 8

INCREASE IN PERFORMANCE

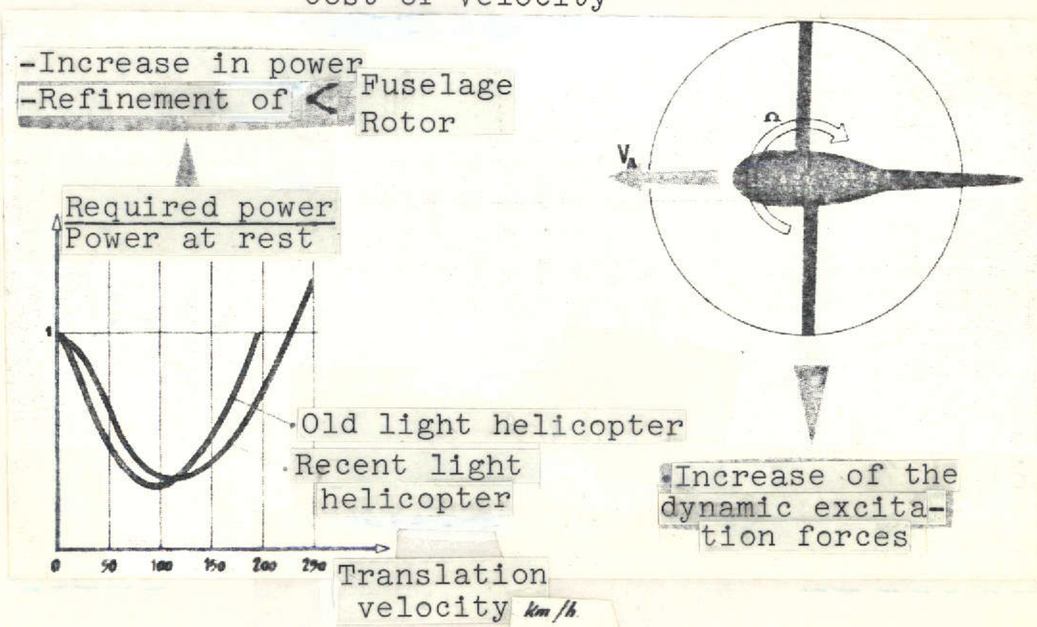
Evolution of the velocity records



Slide 9

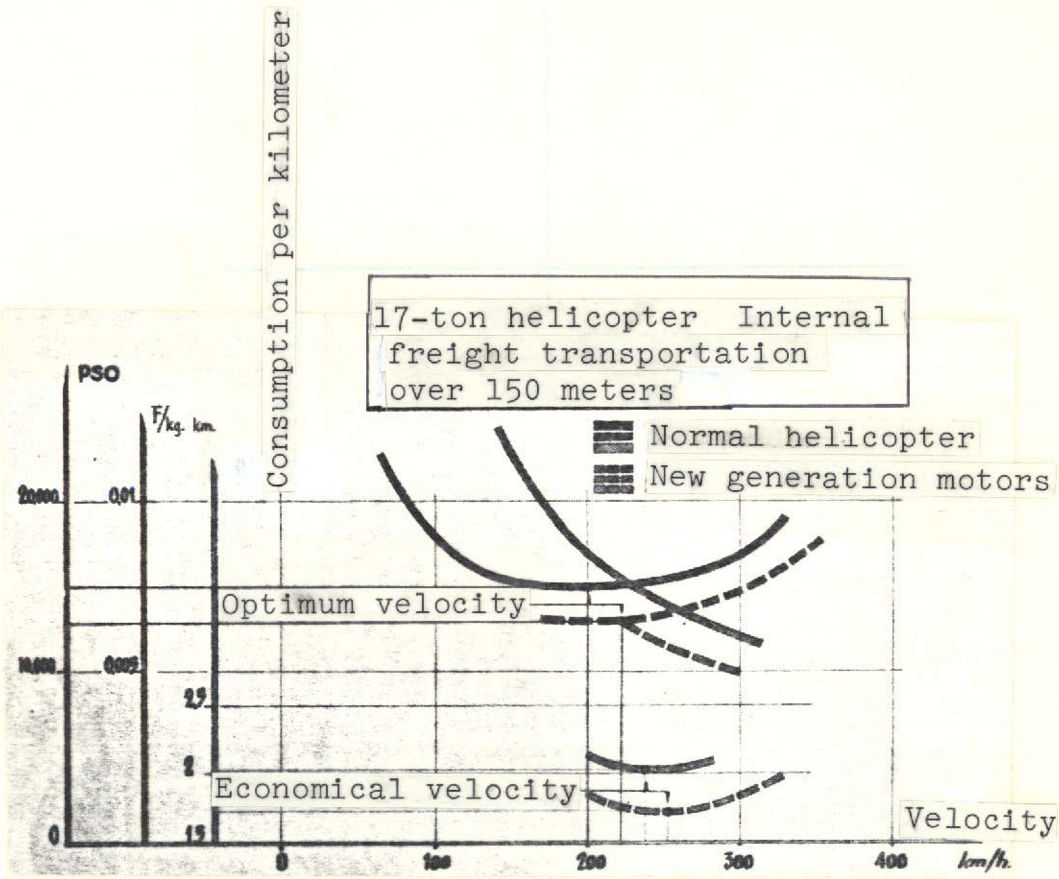
PERFORMANCE INCREASE

Cost of Velocity



Slide 10

COST OF PERFORMANCE



Slide 11

/21-17

SAFETY — PROGRAMMED LIFE ELEMENTS

Mathematical theory

Deterioration of surface of bearings and gears:
- Theoretical calculation
- Test stand tests

→ Concept of periodic replacement (programmed life)

Yesterday
Low potential → (Illegible)

But

Today
Accelerated aging-higher potential obtained more rapidly ← (Illegible)

Acquired experience
- optimization of the material
- new concept
- best knowledge of deterioration
- progress in certification methods
- integration of detection and diagnostic methods

→ Tomorrow
Concept of disposal according to the state associated with infinite lifetimes. Fail safe concepts and redundancy concepts.

Slide 12

SAFETY - COMPONENTS WITH LIFETIMES, OPERATING WITH FATIGUE

Mathematical theory initially

The parameters determine the fatigue resistance according to the Gauss law.

Concept of certain lifetime
Risk 10^{-6}

Confidence coefficient of 90%

<u>Yesterday</u>
Finite lifetimes

<u>Today</u>
Infinite lifetimes

Experimental complement

Formulation of the importance of maintenance errors and uncontrolled fabrication errors

<u>Tomorrow</u>

Fail safe and redundancy concepts

Slide 13

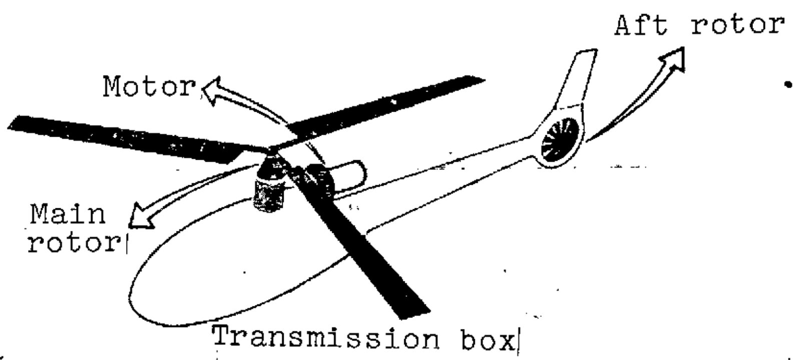
PRICE OF SAFETY

Components with lifetime			Programmed life components
Finite lifetimes Economy Infinite lifetimes Safety	Repercussions on masses negligible, but dimensioning of components is more elaborate initially. Illegible	Negligible mass repercussions but requires a more elaborate dimensioning of the components when conceived plus endurance. Illegible	Programmed life (illegible) Economy Programmed life 2,000
Fail safe and redundancy concepts	Example: Rotor hub. Mass increase of 70 kg (Helicopter: 7000 kg) Illegible	Types of increased surveillance, but gains in exploitation costs. Illegible Example: BTP power chain. Mass increase of 30 kg. (Helicopter: 7000 kg) Illegible	(Illegible) Disposition depending on state Safety Fail safe redundancy

Slide 14

NOISE REDUCTION

A double problem occurs



EXTERNAL SOURCES

Presently: 90 PNdb @ 150 m.
Objective: An improvement of between 15 and 20 PNdB must be obtained for the motors, and 6 to 7 PMdb for the rotors.

INTERNAL SOUND ENVIRONMENT

Presently: 95 to 100 db SIL
Objective: Global required improvement 15 to 20 db SIL.

Slide 15

NOISE REDUCTION

Remedies and Costs

Blades:

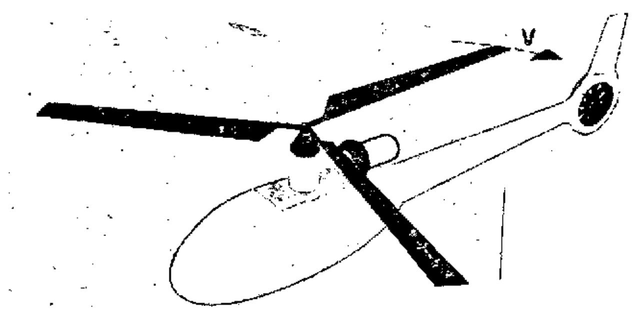
Refinement of the profile, optimization of the plan form
Gain 5 PN db

(Illegible)

Reduction of peripheral velocity
Gain 15 PN db

Aft tail propellor opening:

Optimum g geometry and acoustic treatment of the passage
Gain 5 PN db



Turbine inlet:

Absorption materials and inlet mask
Gain 10 PN db

Loss of 2-3% in motor power

Main box:

Appropriate gearing technology. Transmission shaft must have acoustic improvements.
Gain 20 db SIL

Acoustic optical

Gain 15 db SIL

(Illegible) (Illegible)

Slide 16

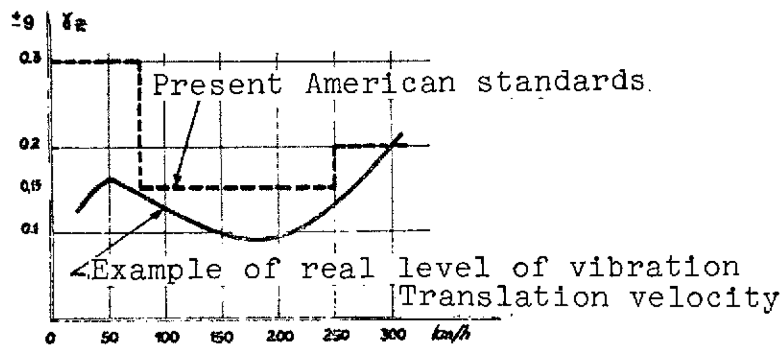
IMPROVEMENT IN THE VIBRATIONAL LEVEL

Fundamental characteristics of helicopter vibrations

<u>Vibrational level consists of:</u>

- Vertical acceleration
- Transverse acceleration
- Longitudinal acceleration
- Vibrational environment

Vibration amplitudes



Vibration frequencies

ω Fundamental = $b\Omega$ = Constant

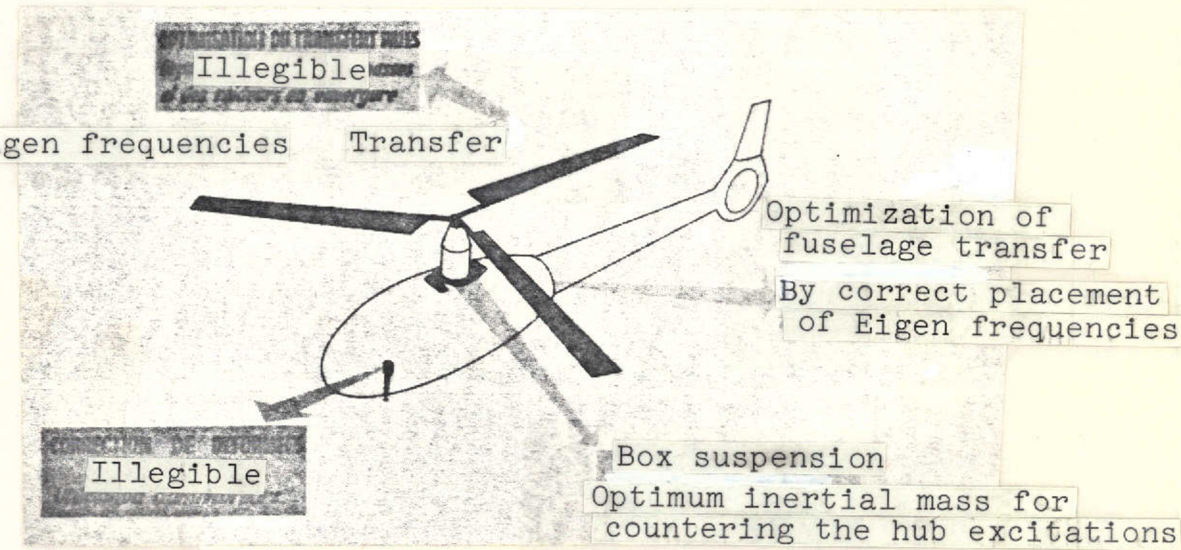
b = number of blades

Ω = Rotor rotation rate

Between 16 to 24 Hz depending on helicopters

IMPROVEMENT IN THE VIBRATIONAL LEVEL

Technical analyses and remedies



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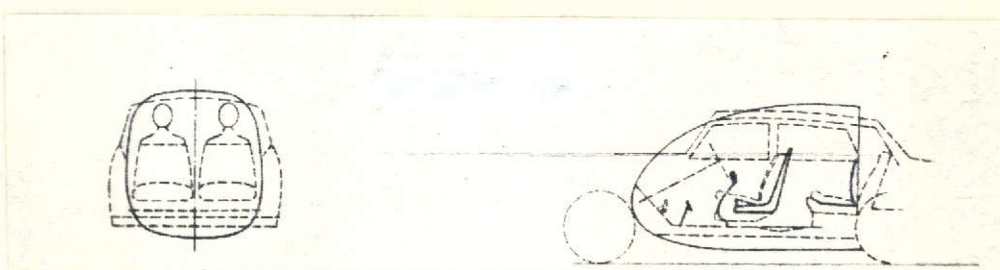
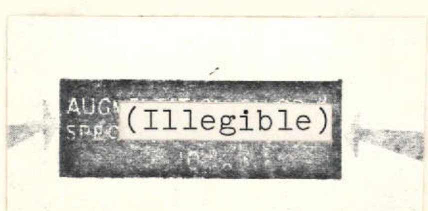
THE PRICE OF COMFORT

Habitability





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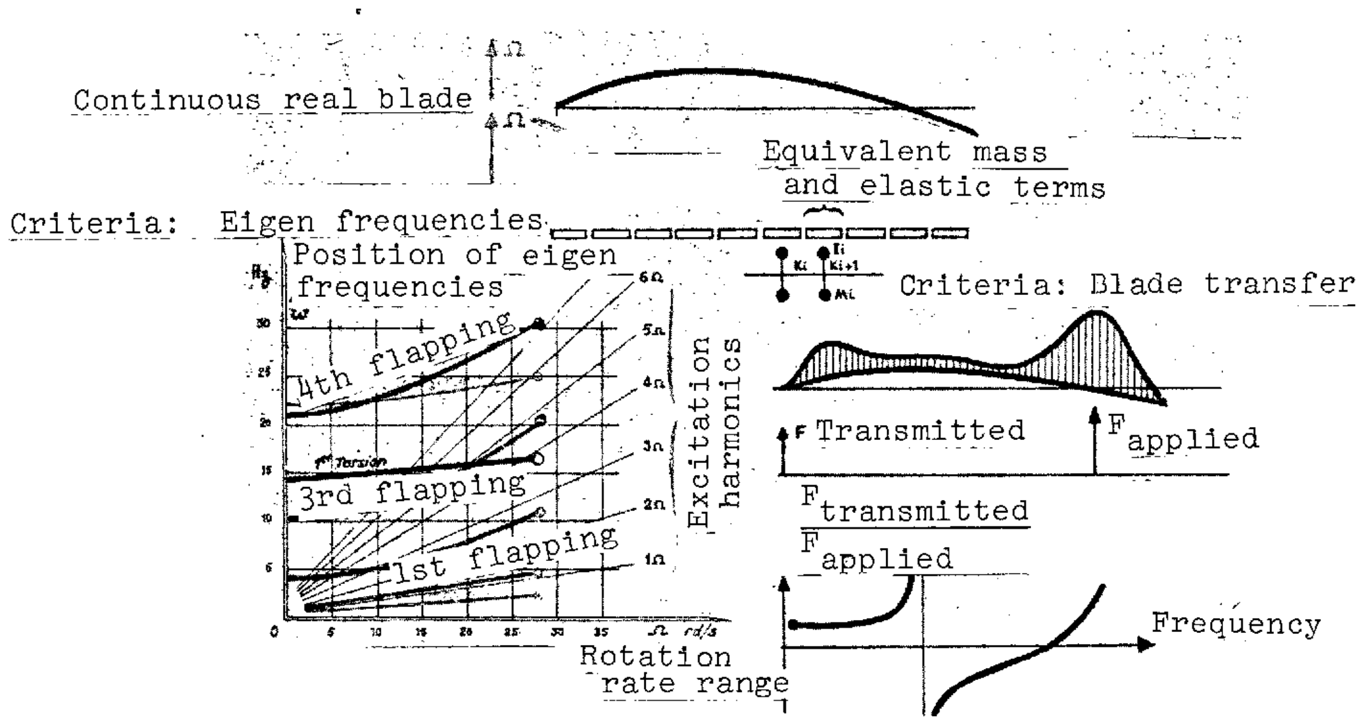
DYNAMIC OPTIMIZATION OF BLADES



Slide 20

AUTOMATIC STRESS ANALYSIS

Old method

Flight outline

Stationary HES 1%
Stationary DES 1%
Transition: 5%
....
100%

Equivalent flight spectrum

CONFIGURATION i → Amplitude of stress a_i
→ Frequency w_i

Manual analysis

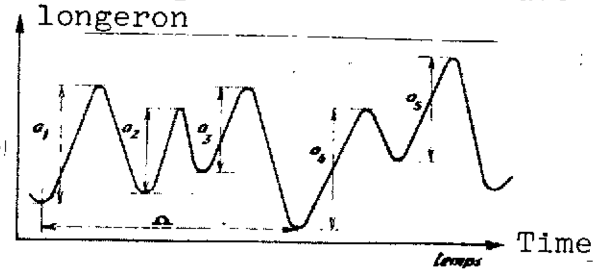
For a time of i% of 1 hour of flight
Damage is e_i (WÖHLER)

Manual calculation
Damage for 1 hour flight = Σe_i (MINER)

Lifetime in hours = $\frac{1}{\Sigma e_i}$

New method

Flapping stresses of a blade longeron



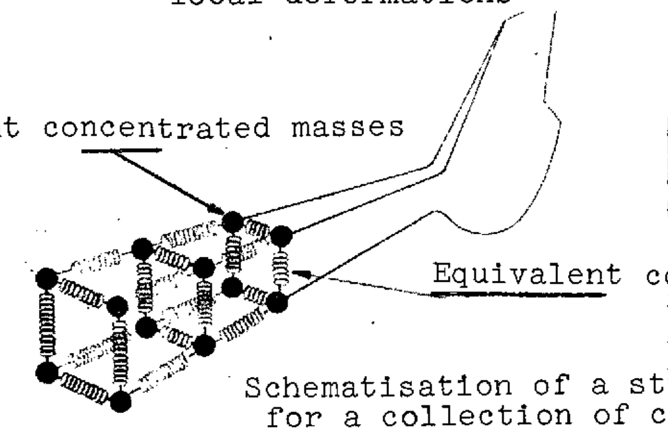
Detection and computer correspondence (WÖHLER)

a_1 → e_1
a_2 → e_2
a_3 → e_3
....
a_i → e_i
....

Computer summation Σe (MINER)

STRUCTURAL ANALYSIS

Makes it possible to calculate eigen frequencies of the structural modes and their overall and local deformations

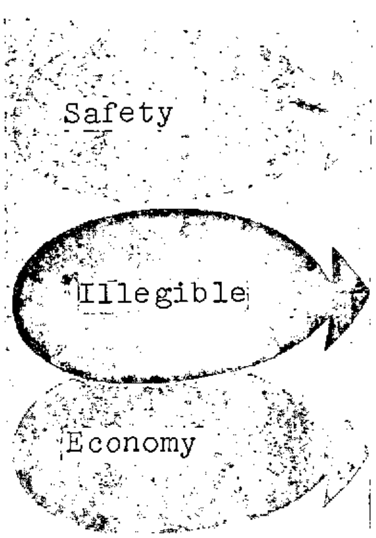


Schematisation of a structure for a collection of concentrated masses. Equivalent springs.

Slide 22

AFT ROTAR WINDOW OPENING

/21-21



- of personnel on the ground
- of the helicopter during nose-up landing
- in case of rear engine failure, possible continuation of flight using lift of the elevator
- No excitation during translation and no instability phenomena

- general fineness of the helicopter
- zero power consumption during translation

- simplified maintenance
- reduced exchange and maintenance costs
- no deicing equipment

Slide 23

DISPOSITION DEPENDING ON STATE

Possible deterioration during use

-Use
-Corrosion -Aging
-Fatigue

-Unfavorable medium
-Poor maintenance
-Etc.

The material can be disposed of depending on the following deteriorations:

At the end of the programmed life

- Often the programmed life of bearings and determined by calculation, tests, on the stand or aging.

Disposition often not justified because equipment is still in a good state.

Or prematurely

- Using traditional surveillance methods during maintenance and during flight

Disposition related to imprecise methods and are often subjective.

Today

Or according to state

- Function of incorporating certain surveillance and diagnostic means in the equipment.

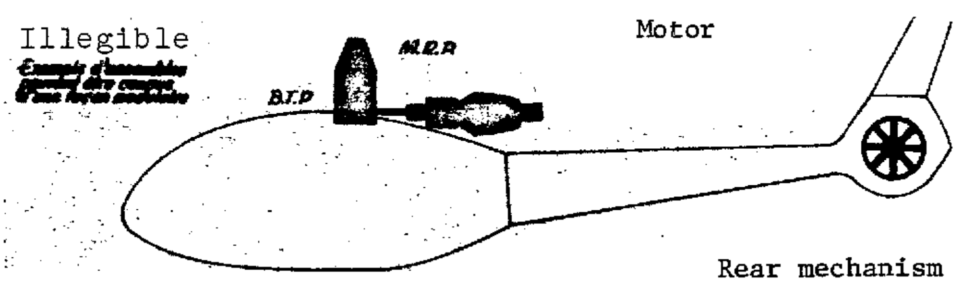
Disposition connected to infinite lifetimes and to increased potential capabilities

Tomorrow

More rational use of equipment

MODULAR CONCEPT

Today ►	Motors or mechanical units whose components cannot be taken apart by the user ►	Disposition of the complete unit for re-vision or repair ►	-Storage Costly and frequent exchange -Long down-time of the complete unit
Tomorrow ►	Motors or mechanical units consisting of modules which are easily removed and can be exchanged "in situ" ►	Rapid interven-tion at the module level if necessary (depend-ing on state) ►	-Improvement in exchange frequency and down-time. -More rational use of equipment



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UTILIZATION OF MASS PRODUCED EQUIPMENT

There are two conflicting views

Traditionally: Respect of aeronautical quality

Today: Balance (safety-price-performance-mass)

	Aeronautical equipment	Non-aeronautical equipment
Price	- Large (small series)	- Low (5 to 10 times cheaper for mass production)
Safety	- Subjected to severe controls. - Satisfies standardized conditions of official agencies	- Several categories to be produced as a function of safety.
Mass	- Light	- Heavy
Performance	- Very high performance - Low performance	- More robust - Generally comparable performances.

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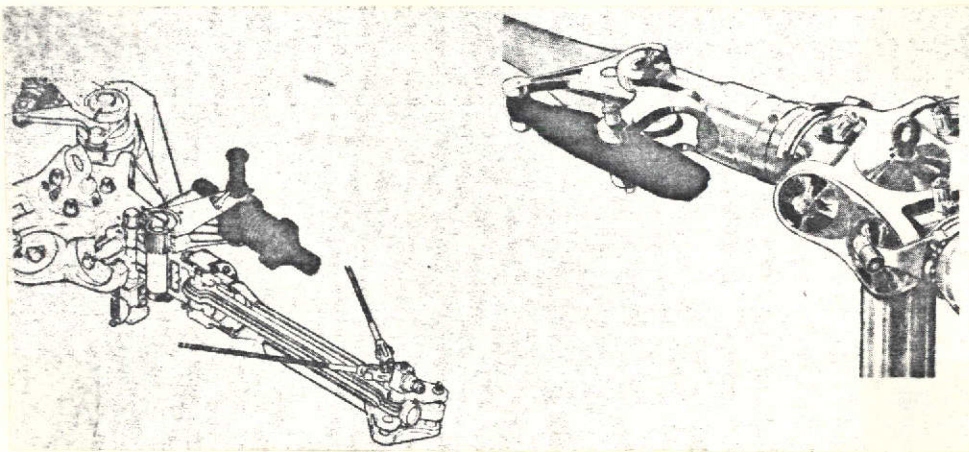
VISOELASTIC MATERIALS /21-22



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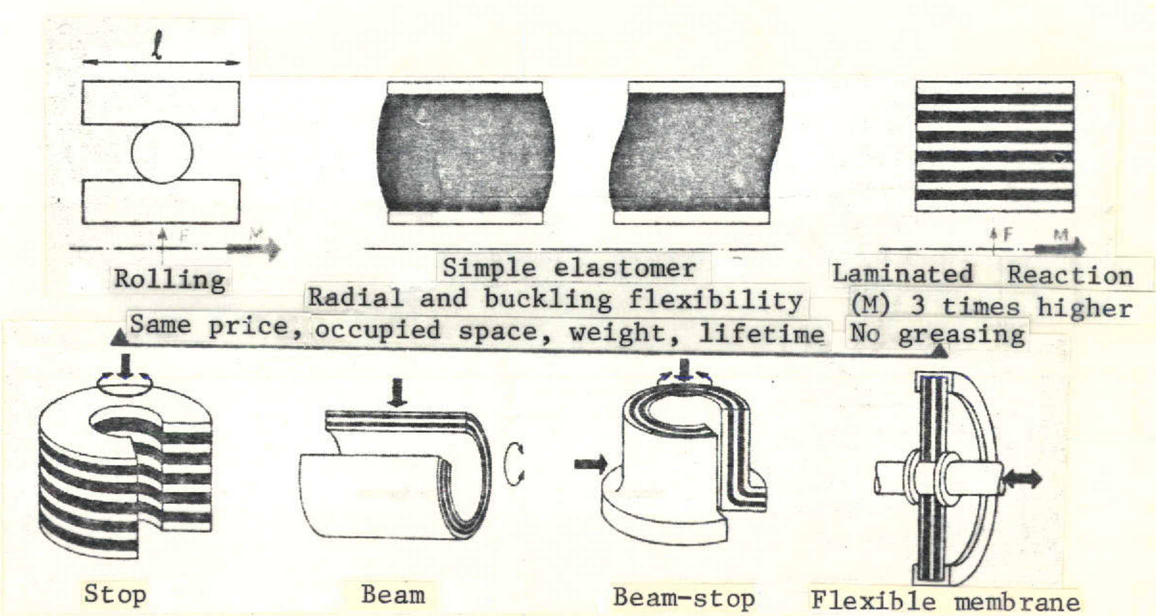
ELASTOMER-METAL LAMINATED MATERIALS

For oscillating motion with normal load



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ARTICULATIONS OF THE MAIN ROTOR HUB

Regions in which roller bearings and dry beams are used

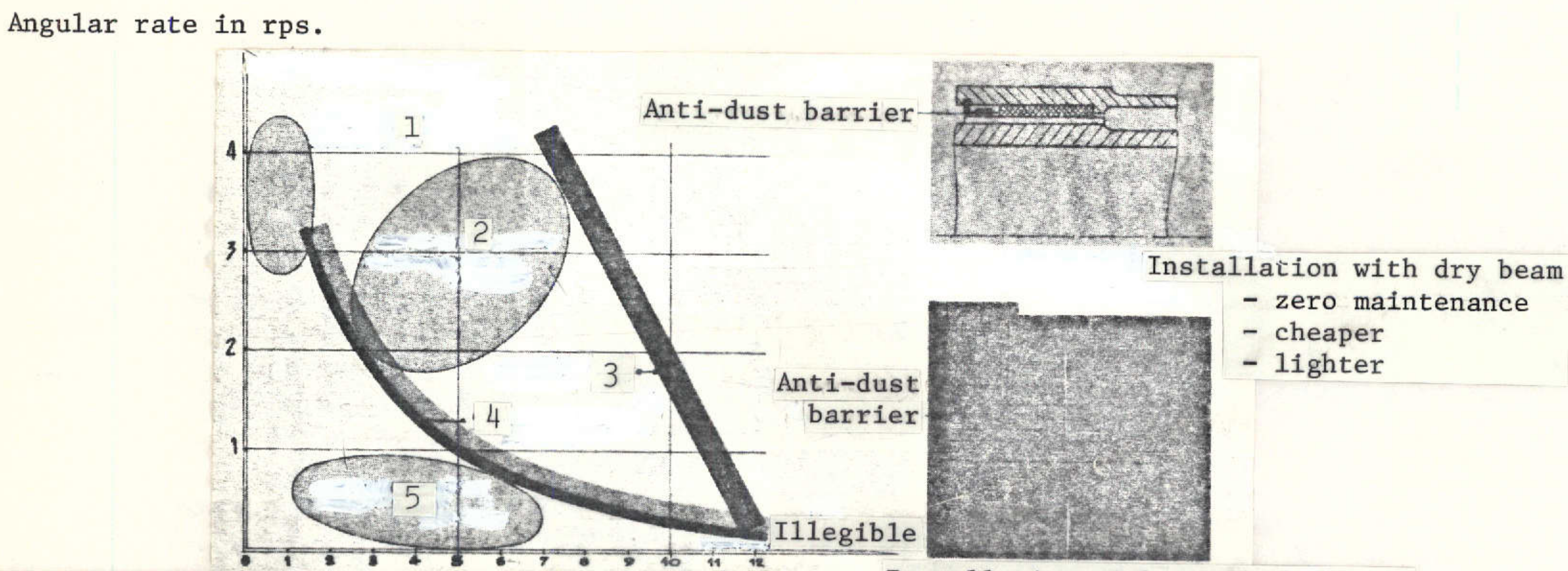

Diagram for alternating motion and 2,000 hour lifetime

Installation with needle bearings

1- Operational range for incidence controls and control links;

2- Operation of flapping articulating members;

3- Limits for using rolling members

4- Limits of use of industrial materials for dry beams;

5- Zone of operation for elongation members;

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16. Abstract
This study is divided into three parts. In the first part, we propose two basic criteria for profitability: the first is the "Specific Cost Price", which is a reference mark for the purchase price of the helicopter; the second is the "Specific Operational Cost", which is a reference mark for the cost of using the helicopter. In the second part, we take up the question of the price paid for the performance, safety, and comfort of present helicopters. In the third part, we evaluate the application of new technologies to the cost-effectiveness trade-off for helicopters.

17. Key Words (Selected by Author(s))

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